S P E C I F I C A T I O N

METHOD AND APPARATUS FOR HIGH-SPEED THICKNESS MAPPING OF PATTERNED THIN FILMS

I. BACKGROUND OF THE INVENTION

This invention relates generally to the field of film thickness measurement, and more specifically, to the field of film measurement in an environment, such as semiconductor wafer fabrication and processing, in which the layer whose thickness is desired to be measured resides on a patterned sample.

Many industrial processes require precise control of film thickness. In semiconductor processing, for example, a semiconductor wafer is fabricated in which one or more layers of material from the group comprising metals, metal oxides, insulators, silicon dioxide (SiO_2), silicon nitride (SiN), polysilicon or the like, are stacked on top of one another over a substrate, made of a material such as silicon. Often, these layers are added through a process known as chemical vapor deposition (CVD), or removed by etching or removed by polishing through a process known as chemical mechanical polishing (CMP). The level of precision which is required can range from 0.0001 μm (less than an atom thick) to 0.1 μm (hundreds of atoms thick).

To determine the accuracy of these processes after they occur, or to determine the amount of material to be added or removed by each process, it is advantageous to measure the thickness of the layers that are on each product wafer, which is generally patterned with fine features. To date, though its desirable effects on product yield and throughput are widely recognized, thickness measurements are only made after certain critical process steps, and then generally only on a small percentage of wafers. This is because current systems that measure thickness on patterned wafers are slow, complex, expensive, and require substantial space in the semiconductor fabrication cleanroom.

The most widely used technique for measuring thin-film thickness on both patterned and unpatterned semiconductor wafers is spectral reflectance. Conventional systems for measuring thickness on patterned wafers employ high-magnification microscope optics along with pattern recognition software and mechanical translation equipment to find and measure the spectral reflectance at predetermined locations.

Examples of this type of system are manufactured by Nanometrics, Inc., and KLA-Tencor. Such systems are too slow to be used concurrently with semiconductor processing, so the rate of semiconductor processing must be slowed down to permit film monitoring. The result is a reduced throughput of semiconductor processing.

A newer method for measuring thickness of patterned films is described in U.S. Patent No. 5,436,725. This method uses a CCD camera to image the spectral reflectance of a full patterned wafer by sequentially illuminated the wafer with monochromatic light of different wavelengths. Because the resolution and speed of available CCD imagers are limited, higher magnification sub-images of the wafer are required to make the desired thickness measurements. These additional sub-images require more time to acquire and also require complex moving lens systems and mechanical translation equipment. The result is questionable advantage in speed and performance over traditional microscope/pattern recognition-based spectral reflectance systems.

Accordingly, it is an object of the present invention to provide a method and apparatus for achieving rapid measurement of film thickness on patterned wafers during, between, or after semiconductor processing steps.

An additional object is a method and apparatus for film thickness measurement which is capable of providing an accurate measurement of film thickness of individual films in a multi-layered or patterned sample.

A further object is an optical method and apparatus for thin-film measurement which overcomes the disadvantages of the prior art.

Further objects of the subject invention include utilization or achievement of the foregoing objects, alone or in combination. Additional objects and advantages will be set forth in the description which follows, or will be apparent to those of ordinary skill in the art who practice the invention.

II. SUMMARY OF THE INVENTION

To achieve the foregoing objects, and in accordance with the purpose of the invention as embodied and broadly described herein, there is provided a method for measuring at least one film on a sample from light reflected from the sample having a plurality of wavelength components, each having an intensity, the method comprising

the following steps: obtaining a set of successive, spatially-contiguous, one-spatial-dimension spectral reflectance images by scanning the wafer with a one-spatial-dimension spectroscopic imager; arranging the resulting series of one-spatial-dimension spectral images to form a two-spatial-dimension spectral image of the wafer; using one or more of the wavelength components of the resulting spectral image to locate preferred measurement locations; and analyzing the spectral data at one or more of the desired measurement locations to determine a parameter such as film thickness.

III. BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a first embodiment of a system in accordance with the subject invention.

Figure 2 illustrates in detail the optical subsystem of the Figure 1 embodiment.

Figure 3 illustrates a second embodiment of a system in accordance with the subject invention.

Figure 4 illustrates an embodiment of a method in accordance with the subject invention.

IV. DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A first embodiment of an imaging system in accordance with the subject invention, suitable for use in applications such as measuring the thickness of transparent or semi-transparent films, is illustrated in Figure 1. Advantageously, the film to be measured ranges in thickness from .001 μm to 50 μm, but it should be appreciated that this range is provided by way of example only, and not by way of limitation. This embodiment is advantageously configured for use with a wafer transfer station 1 to facilitate rapid measurement of a cassette of wafers. The station houses a plurality of individual wafers 1a, 1b, 1c, and is configured to place a selected one of these wafers, identified with numeral 1d in the figure, onto platform 2. This embodiment also comprises a light source 3 coupled to an optical fiber 9 or fiber bundle for delivering light from the light source 3 to the wafer 1d situated on platform 2. Preferably, the light source 3 is a white light source. Advantageously, the light source 3 is a tungsten-halogen lamp or the like in which the output is regulated so that

it is substantially invariant over time. For purposes of illustration, this embodiment is shown being used to measure the thickness of film on wafer 1d, which together comprises a sample, but it should be appreciated that this embodiment can advantageously be employed to measure the thickness of individual films in samples comprising multi-layer stacks of films.

Also included is a line imaging spectrometer 11 comprising a lens assembly 4, slit 5, lens assembly 6, diffraction grating 7, and two-dimensional imager 8. The line imaging spectrometer operates as follows. Light from source 3 passes through fiber bundle 9, and impinges on a film contained on or in wafer 1d. The light reflects off the film and is received by lens assembly 4. Lens assembly 4 focuses the light on slit 5. Slit 5 receives the light and produces a line image of a corresponding line on the wafer 1d. The line image is arranged along a spatial dimension. The line image is received by second lens assembly 6 and passed through diffraction grating 7. Diffraction grating 7 receives the line image and dissects each subportion thereof into its constituent wavelength components which are arranged along a spectral dimension. In one implementation, the spectral dimension is perpendicular to the spatial dimension. The result is a two-dimensional spectral line image which is captured by two-dimensional imager 8. In one implementation, the imager is a CCD, the spatial dimension is the horizontal dimension, and the spectral dimension is the vertical dimension. In this implementation, the spectral components at each horizontal CCD pixel location along the slit image is projected along the vertical dimension of the CCD array.

Additional detail regarding the spectrometer 11 is illustrated in Figure 2 in which, compared to Figure 1, like elements are referenced with like identifying numerals. As illustrated, reflected light (for purposes of illustration, two rays of reflected light, identified with numerals 13a and 13b are shown separately) from wafer 1d is received by lens assembly 4 and focused onto slit 5. Slit 5 forms a line image of the light in which the subportions of the line image are arranged along a spatial dimension. The line image is directed to lens assembly 6. Lens assembly 6 in turn directs the line image to diffraction grating 7. Diffraction grating 7 dissects each subportion of the line image into its constituent wavelength components. The wavelength components for a subportion of the line image are each arranged along a spectral dimension. The wavelength components for the subportions of the line image

are individually captured by two-dimensional imager 8. Thus, the wavelength components for ray 13a are individually captured by pixels 14a, 14b, and 14c, respectively. Similarly, the wavelength components for ray 13b are individually captured by pixels 15a, 15b, and 15c, respectively.

With reference to Figure 1, the light source 3 and the platform 2 are moveable relative to one another. In addition, the platform 2 and spectrometer 11 are moveable in relation to one another. In one implementation, the light source 3 and spectrometer 11 are stationary, and the platform is moveable in the X direction 12.

In operation, light from the fiber bundle 9 is reflected off of the wafer 1d on platform 2 on the wafer transfer station 1. The light is detected by the one-spatial-dimension imaging spectrometer 11, which in turn communicates the spectral and spatial information to the computer 10 over one or more signal lines or through a wireless interface. Spectral reflectance data is continually taken in this way while the wafer 1d is moved under the one-spatial-dimension imaging spectrometer by the platform 2. Once the entire wafer has been scanned in this manner, the computer 10 uses the successively obtained one-dimensional spatial data to generate a two-spatial-dimension image of the wafer. This two-dimensional map can be generated by assembling the measured signal intensity at a single wavelength at each location on the wafer into an image. This two-dimensional image can then be used to find pixels that correspond to specific locations on the wafer, and then the spectral reflectance data that is associated with these pixels can be analyzed using suitable techniques to arrive at an accurate estimate of the thickness of the film. Typically, film thickness is determined by matching the measured spectrum to a theoretically or experimentally determined set of spectra for layers of different thicknesses.

In the foregoing embodiment, although a CCD-based one-spatial-dimension imaging spectrometer is illustrated and described as the means for determining the intensity of the reflected light as a function of wavelength, it should be appreciated that other means are possible for performing this function, and other types of one-spatial-dimension imaging spectrometers are possible than the type illustrated in the figure.

Although the foregoing embodiment is described in the context of semiconductor wafers, and is illustrated in combination with a wafer transfer station for performing this function, it should be appreciated that it is possible to employ this

embodiment in other contexts and in combination with other processing apparatus. Other possible applications include providing thin film scratch resistant and/or antireflective optical coatings to automotive plastics, eyeglass lenses, and the like plastics packaging applications, and applications involving providing proper polymide and resist thicknesses for flat panel display manufacturing. In fact, any application or industrial process in which film measurement is desired is possible for use with the subject embodiment.

Among the primary advantages of the foregoing embodiment is that it is particularly well-suited for real time applications. The reason is that data collection steps employing time-consuming angular or mechanical sweeps of optical components as found in the prior art are eliminated. For example, in the subject embodiment, the one-spatial-dimension imaging spectrometer directly provides digitized values of intensity of the incoming light as a function of wavelength without requiring mechanical sweeping steps or the like. In addition, the number of analytical and pattern recognition steps performed by the computer are limited to only a very few. This is because an image of the entire wafer is made, which eliminates complicated pattern recognition routines that are needed when only small areas of the wafers are viewed at any one time, such as is the case with microscope-based instruments.

A second embodiment of the subject invention, suitable for measuring transparent or semi-transparent films, such as dielectrics deposited upon patterned semiconductor wafers, is illustrated in Figure 3, in which, compared to Figures 1-2, like elements are referenced with like identifying numerals. This embodiment is similar to the previous embodiment, with the exception that the wafer 1d is in a vacuum process or transfer chamber 16, and the wafer motion required for scanning is provided by the transfer robotics 17 that are used to move the wafer inside the process chamber assembly. These transfer robotics allow the wafer 1d to move in the X direction relative to light source 3 and spectrometer 11. Visual access to the wafer 1d is provided by viewport 18. More specifically, light from light source 3 is directed to impinge upon wafer 1d via fiber bundle 9 through viewport 18. In addition, light reflected from wafer 1d is received by spectrometer 11 after passage through viewport 18. As transfer robotics 17 move the wafer 1d through the transfer station 16 as part of the CVD process, spectral measurements are successively taken from successive

portions of wafer 1d and provided to processor 10. Processor 10 may successively perform calculations on the data as it is received or may do so after all or a substantial portion of the wafer 1d has been scanned. As with the previous embodiment, processor 10 may use this data to estimate film thickness or perform end point detection.

In addition to the advantages listed for the first embodiment, this embodiment has the additional advantage of providing rapid in-line film thickness measurements taken during the normal transfer motion of the wafers between processes. This means that measurements can be made without slowing down the process and thus will not negatively impact throughput. Also, because the unit is compact and can be placed upon existing equipment, very little cleanroom space is required. Additionally, because there are no added moving parts, the system is very reliable. Moreover, because it sits entirely outside of the vacuum chamber, it introduces no particles or contamination to the fabrication process.

Although the foregoing embodiment is described in the context of CVD processing of semiconductor wafers, and is illustrated in combination with a CVD station for performing this function, it should be appreciated that it is possible to employ this embodiment in other contexts and in combination with other processing apparatus. In fact, any application or industrial process in which in-line film measurement is desired, i.e., film measurement during an ongoing industrial process, is possible for use with the subject embodiment.

An embodiment of a method in accordance with the invention is illustrated in Figure 4. As illustrated, in step 20, a line image of a corresponding line of a film is formed. The line image image has subportions arranged along a spatial dimension. Step 20 is followed by step 21, in which subportions of the line image are individually dissected to their relevant constituent wavelength components. The wavelength components for a subportion are arranged along a spectral dimension. Step 21 is followed by step 22, in which data representative of the wavelength components of the subportions is individually formed. The process may then be repeated for successive lines of the film until all or a selected portion of the film has been scanned. Throughout or at the conclusion of this process, estimates of film thickness or endpoint detection or other statistics may be formed from the assembled data.

EXAMPLES

In an exemplary embodiment of the subject invention, suitable for use in a CVD environment, the light source 3 is a tungsten/halogen regulated light source, manufactured by Stocker & Yale, Inc., Salem, New Hampshire.

Fiber/fiber bundle 9 in this embodiment is a bundle configured into a line of fibers to provide uniform illumination along the measured surface. Such a fiber optic "line light" is manufactured by several companies, Stocker & Yale being a prime example.

This example is configured for use with CVD processing system Model P5000 manufactured by Applied Materials Inc., Santa Clara, California. An optically clear viewport 18 is provided in the standard P5000 configuration.

The line imaging spectrometer 11 in this example is manufactured by Filmetrics, Inc., San Diego, California, the assignee of the subject application. In this spectrometer, the imager 8 is a CCD imager incorporating a time delay and integration line scan camera manufactured by Dalsa Inc., Part No. CT-E4-2048. The transmission diffraction grating 7 is manufactured by Optometrics, Ayer, MA, Part No. 34-1211. The lenses 4 and 6 are standard lenses designed for use with 35 mm-format cameras. The line scan camera is operated in area scan mode, with only the first 48 rows of pixels read out. This results in a data read rate greater than 700 frames per second. Forty-eight rows of spectral data are sufficient for measurement of thicknesses in the range required for CVD deposited layers.

It has been found that this exemplary embodiment yields a thickness accuracy of ± 1 nm at a 1000 nm film thickness, at a rate of five seconds per wafer scan.

Additional advantages and modifications will readily occur to those of skilled in the art. The invention in the broader aspects is not, therefore, limited to the specific details, representative methods, and illustrative examples shown and described. Accordingly, departures may be made from such details without departing form the spirit or scope of applicant's general inventive concept, and the invention is not to be restricted except in light of the appended claims and their equivalents.